TSUNAMI GENERATED BY THE VOLCANO ERUPTION ON JULY 12-13, 2003 AT MONTSERRAT, LESSER ANTILLES

Efim Pelinovsky[1], Narcisse Zahibo[2], Peter Dunkley[3], Marie Edmonds[4], Richard Herd[4], Tatiana Talipova[1], Andrey Kozelkov[5], Irina Nikolkina[5]

1) Laboratory of Hydrophysics and Nonlinear Acoustics, Institute of Applied Physics, Nizhny Novgorod, Russia (E-mail: enpeli@hydro.appl.sci-nnov.ru)
2) Laboratoire de Physique Atmosphérique et Tropicale, Département de Physique , Université Antilles Guyane, Pointe-à-Pitre, France (E-mail: narcisse.zahibo@univ-ag.fr)
3) Montserrat Volcano Observatory, Montserrat (Email: pnd@bgs.ac.uk)
4) Montserrat Volcano Observatory, Montserrat; currently USGS-Hawaiian Volcano Observatory, Hawaii USA (Email: medmonds@usgs.gov)
5) Applied Mathematics Department, State Technical University, Nizhny Novgorod, Russia (E-mail: ask@land.ru)

ABSTRACT

A major collapse of a lava dome occurred at the Soufrière Hills Volcano (Montserrat, Lesser Antilles), culminating late in the evening (11:35 PM local time) on July 12, 2003 (03:35 GMT on 13 July). This generated a tsunami, which was recorded on Montserrat 2-4 km from the generating area and Guadeloupe, 50 km from Montserrat. Results of field surveys are presented. Tsunami wave height on Montserrat may have been about 4 m according to the location of a strandline of charred trees and other floating objects at Spanish Point on the east coast of the island. The wave height on Guadeloupe according to "direct" witnesses was about 0.5-1 m at Deshaies and near Plage de la Perle. The tsunami at Deshaies caused the scattering of boats as confirmed by fishermen and local authorities. Data from the field survey are in agreement with the predicted tsunami scenario obtained by numerical simulation.

1. Introduction

Soufrière Hills Volcano is located on Montserrat, Lesser Antilles (16.72°N, 62.18°W); see Figure 1. The volcano is currently undergoing a prolonged eruption, which began in July 1995 and has caused widespread devastation to the southern part of the island, including the destruction of the airport and the capital of Plymouth. There have also been a number of fatalities. The island’s population fell from about 11,000 to 3,500 during the early part of the eruption, but has increased slightly in recent years to about 4,600. Buffonge in series of books (1996 – 1998) provides a chronicle of Montserrat’s society experience with the volcano; see also, Pattullo, 2000.

Figure 1. Chart of Montserrat, Lesser Antilles

The first phase of the eruption lasted from July 1995 until March 1998 and is described in a series of short papers published in Geophysical Research Letters (Young et al. 1998) and in a comprehensive collection of papers in a Geological Society of London memoir (Druitt and Kokelaar, 2002). The largest single event of the first phase of the eruption occurred on 26 December 1997, when the southern wall of the old summit crater failed due to loading by the lava dome. This generated a debris avalanche and resulted in the rapid collapse of the active lava dome, unleashing a powerful pyroclastic density current and a volcanic blast, as well as generating a small tsunami.

A period of stagnation in the eruption began in March 1998 and continued until November 1999 when extrusion of lava recommenced and marked the onset of the second phase of dome growth. During this second phase the dome grew and collapsed several times.

By mid-2003 the lava dome had grown to an unprecedented size, having a volume of about 200 million m^3 and a general summit elevation of around 1100 m. On 12-13 July the dome underwent the largest collapse of the entire eruption to date. This was a prolonged event. Continuous pyroclastic flows (composed of hot rocks, ash and gas) began in the Tar River Valley on the eastern side of the volcano at 09:30 local time (13:30 GMT) on 12 July (Herd et al., 2004). From 10:45 onwards these reached the sea and at 18:30 the flows became larger and more energetic as the collapse progressively cut back into the hotter interior of the dome. The collapse reached its most energetic phase between 21:50 12 July and 0:50 13 July when a sequence of very large pyroclastic flows entered the sea and pyroclastic surges traveled up to 3 km across the surface of the sea. The climax of the collapse occurred at 23:35 when a very large pyroclastic flow impacted the sea and pyroclastic surges devastated 7 km^2 on the NE flank of the volcano (Edmonds et al., 2004). A tsunami appears to have been generated at this stage. A number of explosive events also took place, with the largest occurring during the climax of the collapse, producing ash clouds to an altitude of 15 km. In total over 120 million m^3 of material was removed during the collapse, leaving a large amphitheatre-shaped scar in the dome, which is open to the east above the Tar River Valley. The valley itself was also extensively modified with a deep canyon eroded by the pyroclastic flows. Various photos of this event can be found in the website of the Montserrat Volcano Observatory (http://www.mvo.ms). One of the photos of the pyroclastic flow entering sea is shown in Figure 2.

Figure 2. Pyroclastic flow down the Tar River valley on 12th July 2003 Photograph M Edmonds © NERC

Large dome collapses on Montserrat have produced tsunami waves on two occasions during the current eruption. The earlier dome collapse of December 26, 1997 (Boxing Day Collapse) produced an avalanche in the White River Valley (for location, see Figure 1). This resulted in a large amount of debris entering the sea and the generation of a tsunami. Heinrich et al (2001) presented numerical simulations of this debris avalanche. The wave rolled northwards parallel to the coast, ending up at Old Road Bay, 10 km from the landslide site (see Figure 1), where it pushed boats and trailers some distance up on to the shore (Buffonge, 1998). Lander et al (2002) gives the following description of the tsunami: "The wave was estimated to have been about 1 m higher than the road which lies 2-m above water level, and to have moved inland a maximum distance of 80 m. A variety of objects, including a small wooden boat, a roof to a shelter, and a stone table were displaced several meters inland and a large log was carried even farther by the wave. Impact marks up to 1 m were also reported on the side of palm trees facing the sea. The grass was oriented in such a way as to indicate the retreat of the wave. An observer reported seeing the sea move out and then back in, which is typical of a landslide-generated tsunami. The focusing of the wave at Old Road Bay may be attributed to the peculiarities of wave behavior along a coastline and the abrupt change of coast direction at Old Road Bay. The wave moved inland here, because the coast abruptly changes its direction, and the wave moving parallel to the coast would have met the shore head-on. Also, the shallow offshore bathymetry and onshore topography in the area aided extended wave runup." There is no record of this tsunami on the neighboring islands of Antigua, Guadeloupe, and St Kitts.

The main goal of this paper is to present the data of a field survey conducted on the islands of Montserrat, Guadeloupe and Antigua following the very large collapse of the dome of 12-13 July 2003. The results of numerical simulations of tsunami propagation related to this event are also discussed.

2. Numerical simulation of tsunami waves generated at volcano eruption in Montserrat

A hypothetical tsunami event due to collapse of the lava dome in the Tar River Valley and to a sudden entry of a debris avalanche into sea was in fact modelled numerically by Heinrich et al (1998, 1999). Considering a debris avalanche volume of $40 \cdot 10^6$ m^3 (the same volume is estimated for the debris avalanche of 26 December 1997) entering the sea at speed of 40 m/s, their modelling suggested that most of the wave energy propagates in the open sea in the slide direction, i.e. towards Guadeloupe and Antigua. The distribution of the maximum water surface elevation is presented in Figure 3 taken from Heinrich et al (1998). Along the coast of Montserrat (in fact, near the coast at a depth of 10 m), the computed wave heights are maximal in the epicentral zone (6-10 meters), and 1-2 m at distances of about 10 km from the generation area (Heinrich et al, 1998). According to the modelling, tsunami waves of 2–3 m could reach Guadeloupe and Antigua (50 km from Montserrat) in 10 minutes; see Figure 4 (Heinrich et al, 1999).

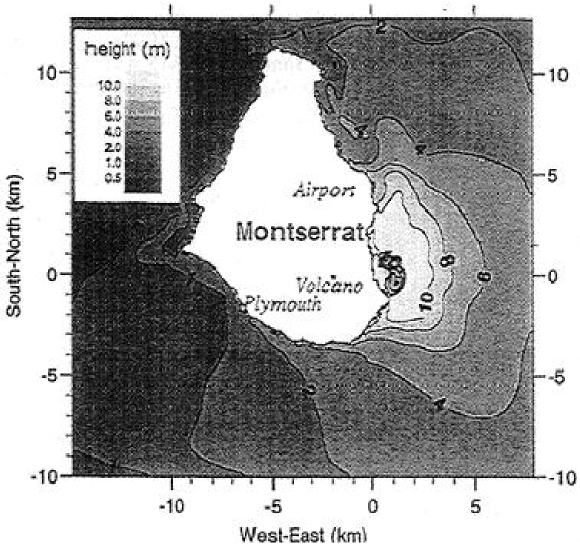

Figure 3. Maximum water surface elevation on Montserrat coast during the tsunami propagation (Heinrich et al, 1998)

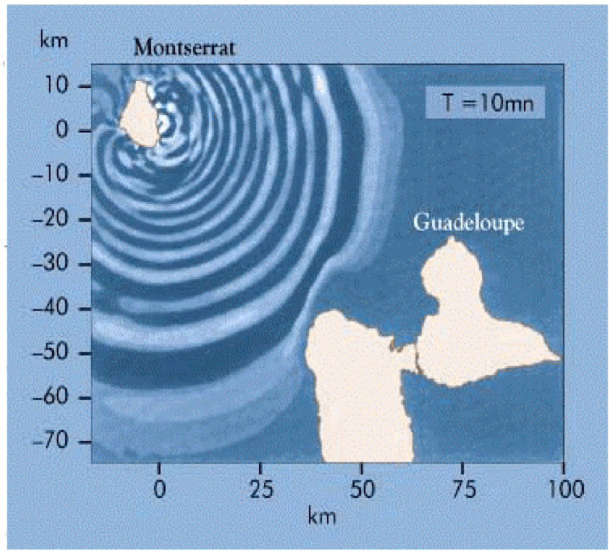

Figure 4. Tsunami wave propagation from Montserrat (Heinrich et al, 1999)

We estimate roughly a comparable distribution of the tsunami wave amplitude along the coasts of Guadeloupe, Antigua and St Kitts. In our simulations the nonlinear shallow water equations are applied based on the numerical code TUNAMI, recently used to study the 1867 Virgin Island tsunami in the Lesser Antilles (see, Zahibo et al., 2003a). The bathymetry of the Eastern Caribbean is taken from the GEBCO Digital Atlas (British Oceanographic Data Centre) with mesh size 1.5 km. As in the modelling of Heinrich et al (1998), the runup stage is not simulated and complete reflection is calculated for the last sea points. The tsunami source is modeled by the initial upward water displacement (up to 10 m) in the "sea" part of the circle of diameter 2 km located at the mouth of the Tar River (16.71N, 62.14W). Such a source was chosen to demonstrate wave propagation along the coasts of neighboring islands far from the source. Figure 5 shows the directivity of the tsunami propagation. It is clearly seen that the tsunami waves mainly propagate towards Antigua and Guadeloupe and relative weakly towards Nevis and Barbuda, as was predicted in the more exact computing by Heinrich et al (1998, 1999). According to our calculations, the maximum wave amplitudes are 1.6 m at Guadeloupe, 1.9 m at Antigua (1.9 m), 1.2 m at Nevis and 0.9 m at Barbuda. We should stress that these results are very sensitive to the properties of the tsunami source (water displacement and directivity). Although the tsunami source model is only approximate, the comparable wave amplitudes in various coastal locations can be used to select zones where the tsunami effect may be expected to be large. Therefore, from our computing we may conclude that wave heights of the 12-13 July 2003 Montserrat tsunami at Guadeloupe and Antigua were approximately the same, and by comparison were at least twice as small at Nevis and Barbuda. We have calculated the relative wave height distributions along the coast of neighboring islands (Figure 6), normalized on its maximum value for each island. This demonstrates that the 12 July 2003 tsunami should have been manifested on the northern capes and western coast of Guadeloupe, western coast of Antigua, and, perhaps, south-eastern coast of Nevis and west-southern coast of Barbuda.

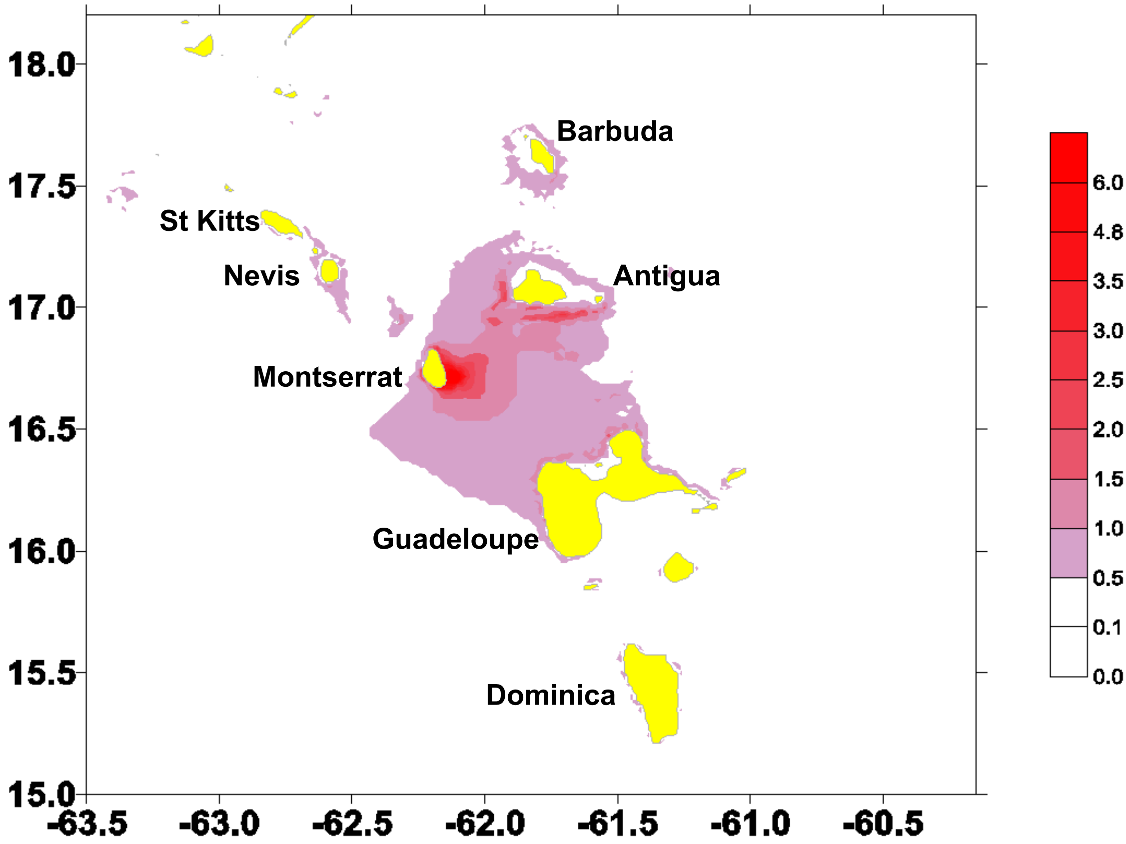

Figure 5. Directivity diagram at the isotropic source

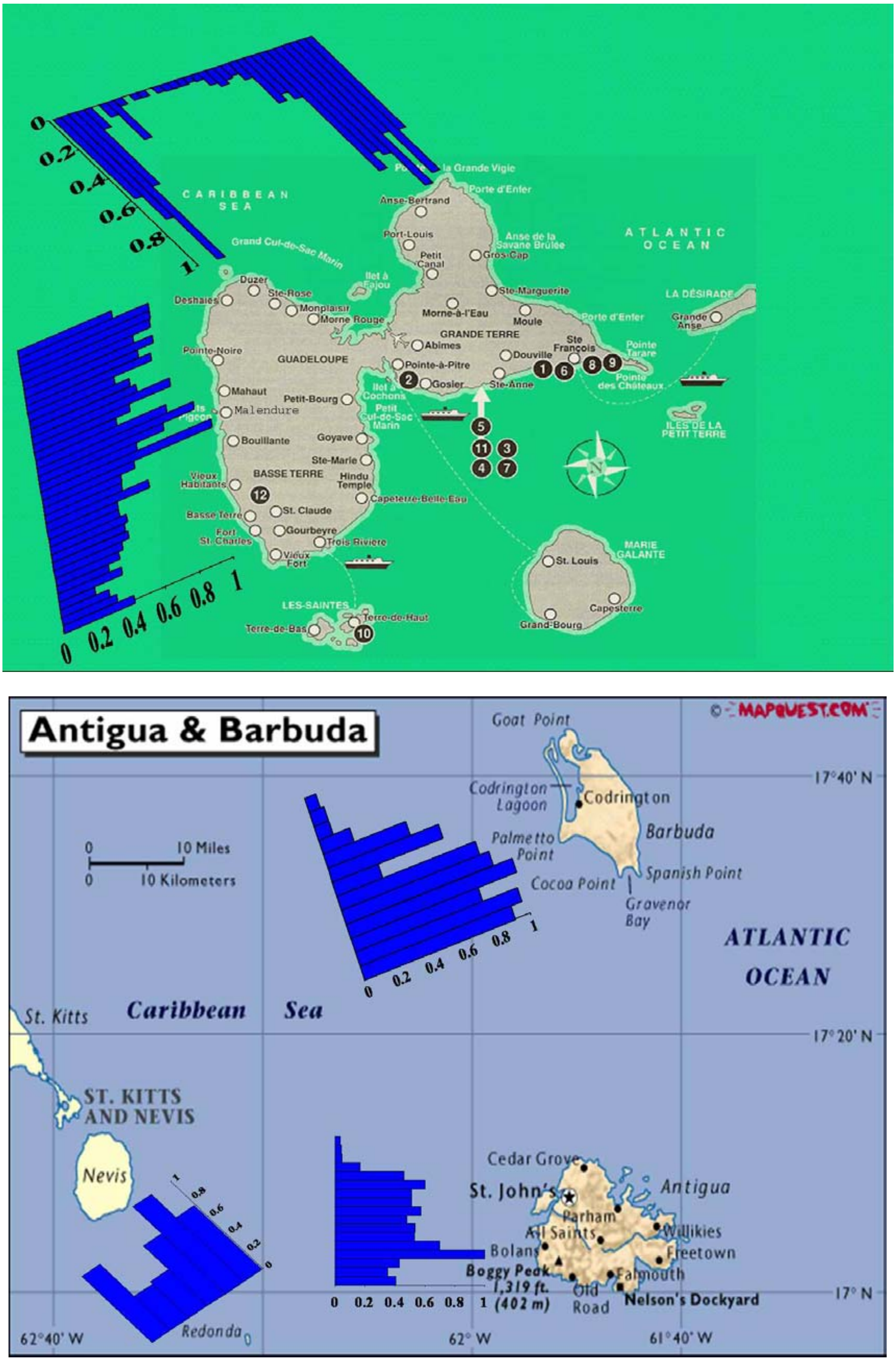

Figure 6. Distribution of the relative wave height along the coasts of Guadeloupe, Antigua, Barbuda and Nevis

3. Field survey data

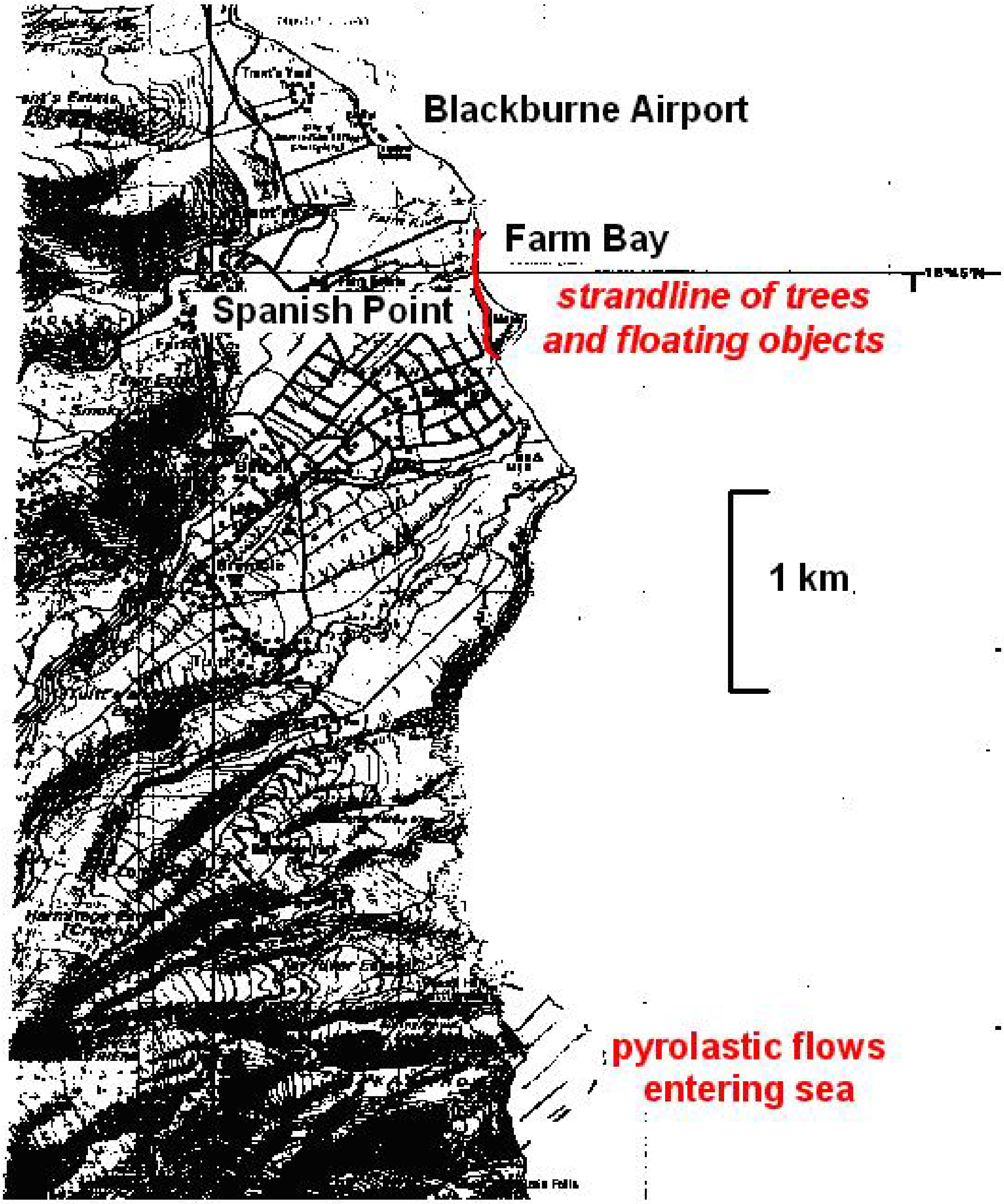

Figure 7. Chart of the area where strandline of trees and floating objects have been found

The first field survey of the coastal area at ***Montserrat*** was conducted in the middle of September 2003 by staff of the Montserrat Volcano Observatory. A strandline of charred trees and other floating objects was found at Spanish Point on the coast at Farm Bay (16.737N, 62.153W) approximately 3-4 km north of the mouth of the Tar River Valley where the pyroclastic flows impacted the sea on 12-13 July; see Figure 7 for the detailed chart of this area. The strandline is located between about 100-150 m from the shoreline at a height of 4 m above sea level (eye estimates). Cyclone activity was high in September 2003 when two hurricanes passed near Montserrat to the north. These were: "Fabian", category 4, September

3; and "Isabel", category 4-5, September 13. Their tracks taken from the *NOAA Tropical Prediction Center* (UNISYS), are shown in Figure 8. It is possible therefore that the strandline of charred trees may have resulted from a tsunami related to the dome-collapse, as well as from a storm surge. Taking into account the local character of this phenomenon near Tar River Valley, the tsunami origin is preferable. A second field survey around Spanish Point was conducted by the writers in January 2004, at which time the strandline was still apparent (Figure 9).

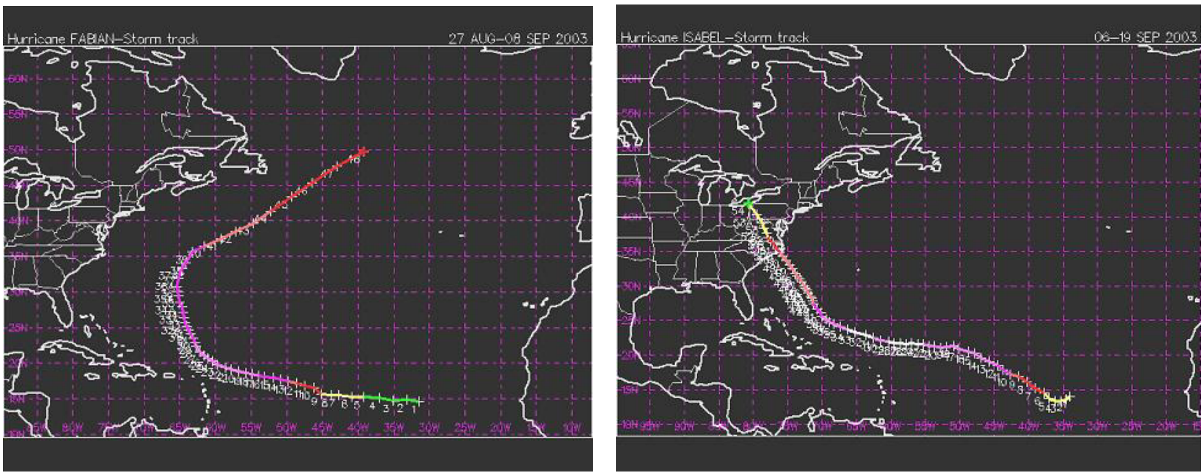

Figure 8. Tracks of hurricanes: “Fabian” (left) and “Isabel” (right)

Figure 9. Strandline of charred trees and other floating objects on the coast at Farm Bay (Spanish Point)

The field survey in ***Guadeloupe*** was conducted in November 2003. First of all, we should mention that there is no tide gauge in Guadeloupe now to provide quantitative information. Also there was no information on the tsunami in the local newspaper “France - Antilles”, except for a report from Montserrat concerning the eruption on the night of July 12-13, 2003. We could not find direct traces of tsunami manifestation, but obtained witness reports. These were obtained from three locations on the western coast of Guadeloupe at Deshaies, Malendure, and Vieux Habitans (for locations see Figure 6). The distance between Deshaies and Vieux Habitans is about 27 km. At the port of ***Deshaies*** (Figure 10a), and in the mouth of the river Deshaies (Figure 10b) fishermen on the next morning (13 July) found that approximately 10 boats were scattered in the port and river and had been moved onto the land (up to 15 m). Some of these were slightly damaged. The height of the wall in the place of the boat mooring in the port is 40 cm. One small boat, moored in the mouth of the river Deshaies, was carried for more than 60 meters up the river to the bridge (Figure 10c). The customers of the restaurant “Note Bleue”, who were celebrating a wedding, were surprised by an abrupt rise of water in the mouth of the river of Deshaies during the night of the 12-13 July, which occurred sometime between 23.00 and 01.00 (local time). The appearance of the tsunami corresponds approximately to the climax of the dome collapse on Montserrat between 11-12 PM. Water overflowed the coast of the river mouth (60 cm); see Figure 10d. No noise of a wave or wind accompanied this phenomenon. The Police investigated the area at 02.00 (July 13). Some people, referred to as "direct" witnesses, reported that the water rose 1.5 m near the entry to the port and surged 25 m inland. The duration of the wave, which broke on the beach, was about 1 min, and is reported to have arrived at 23:30, although this information is not from first hand reports.

Figure 10. Deshaies, a) port, b) the river mouth, c) 60 m upstream, where the boat was found near the bridge, d) restaurant in the river mouth, where the beach was overflowed

On the ***Plage de la Perle***, a few kilometers to the north of Deshaies, a shopkeeper told us that on the next morning he found that the sand level on the beach had increased by up to 50 cm. We should add that this beach is protected by a coral reef near the shoreline. At ***Malendure*** (14.5 km to the south of Deshaies), where according to our simulations wave height should have been at a maximum, the tide that night rose several meters at certain places along the coast where it penetrated for 20 m inland. The sea rose 46 centimeters on the foot of the pontoon of Malendure (Figure 11). ***At Vieux Habitans*** (13 km to the south of Malendure and 27 km from Deshaies), the water rose up to 60 cm. Unfortunately, we were not able to find "direct" witnesses of the tsunami at Malendure and Vieux Habitans. According to the information collected at these localities on Guadeloupe, we may conclude that the water rise at Deshaies was due to a real tsunami with a confirmed wave height of about 0.5-1 m. The reliability of the information on the tsunami in other places (Malendure and Vieux Habitants) is not quite clear. The water rise in these places was probably not recorded due to it being nighttime and also because of the low amplitude of the wave.

Figure 11. Pontoon of Malendure (46 cm above sea level)

We visited ***Antigua*** (St John's and Jolly Harbour (near Bolans) in January 2004 (see Figure 6 for locations, but were not able to find any reports of the tsunami in these places.

4. Conclusion

The climax of the large dome collapse at the Soufrière Hills Volcano, Montserrat occurred late in the evening (23:35 local time) on 12 July, 2003 (03:35 GMT on 13 July). The impact of a large pyroclastic flow on the sea generated a tsunami, which was recorded on **Montserrat**, 2-4 km from generating area and **Guadeloupe**, 50 km from Montserrat. The results of the field surveys are presented. The wave height on Montserrat may have been about 4 m according to the location of the strandline of charred trees and other floating objects at Spanish Point. The wave height on Guadeloupe according to "direct" witnesses was about 0.5-1 m at Deshaies and near Plage de la Perle. The tsunami at Deshaies scattered boats, as confirmed by fishermen and local authorities. Data from the field survey are in agreement with the predicted tsunami scenario of Heinrich et al (1998, 1999) and our simulations.

It is important to point out that the 2003 tsunami is the third event recorded on Guadeloupe during the last 150 years. The two other events include: the catastrophic 1867 tsunami, when waves generated on the Virgin Islands approached Guadeloupe with heights of about 10 m at Deshaies and St Rose; and the weak 1985 tsunami, when a wave several centimeters high was recorded by the tide gauge at Basse-Terra (Zahibo et al., 2001, 2003; Lander et al., 2002). The tsunami risk for the Lesser Antilles should therefore not be ignored and should be evaluated. Such work is now in progress (Zahibo & Pelinovsky, 2001; Zahibo et al, 2003b)

Acknowledgements. Particular support from EGIDE (04500YH), INTAS (01-2156) and RFBR (02-05-65107 and 03-05-64975) is acknowledged. For relevant authors this paper is published with the permission of the Director, British Geological Survey (NERC), and the Director, Montsterrat Volcano Observatory.

References

Buffonge, C. *Volcano!* Books 1-4. Ideal Printers, Montserrat, 1996-1998.

Druitt, H.T.H., and Kokelaar, B.P. The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. *Geological Society Memories*, No. 21. Geological Society of London, 2002.

Edmonds, M., Herd, R. A. and Strutt, M. H. Tephra deposits arising from the lava dome collapse and explosions 12-15 July 2003 at Soufrière Hills Volcano, Montserrat, West Indies. *Journal of Volcanology and Geothermal Research*, 2004 (submitted).

Heinrich, Ph., Mangeney, A., Guibourg, S., and Roche, R. Simulation of water waves generated by a potential debris avalanche in Montserrat, Lesser Antilles. *Geophysical Research Letters*, 1998, vol. 28, 3697-3700.

Heinrich, Ph., Roche, R., Mangeney, A., and Boudon, G. Modeliser un raz de maree cree par un volcan. *La Recherche*, 1999, vol. 318, 67-71.

Heinrich, Ph., Boudon, G., Komorowski, J.C., Sparks, R.S.J., Herd, R., and Voight, B. Numerical simulation of the December 1997 debris avalanche in Montserrat, Lesser Antilles. *Geoph. Research Letters*, 2001, vol. 28, No. 13, 2529-2532.

Herd, R. A., Edmonds, M., Sanchez, J. and Bass, V. A large dome collapse and explosive activity 12-15 July 2003 at Soufrière Hills Volcano, Montserrat, West Indies. *Journal of Volcanology and Geothermal Research*, 2004 (submitted).

Lander, J.F., Whiteside, L.S., and Lockridge, P.A. A brief history of tsunami in the Caribbean Sea. *Science of Tsunami Hazards*, 2002, vol. 20, 57-94.

Pattullo, P. *Fire from the Mountain. The tragedy of Montserrat and the betrayal of its people*. Constable, London. 2000.

UNISYS. *Atlantic Tropical Storm Tracking by Year.* Based on data from the Tropical Prediction Center, NOAA. http://www.weather.unisys.com/hurricane/atlantic/index.html

Zahibo, N., Pelinovsky, E. Evaluation of tsunami risk in the Lesser Antilles. *Natural Hazards and Earth System Sciences*, 2001, v. 1, No. 4, 221-231.

Zahibo N., Pelinovsky E., Yalciner A., Kurkin A., Koselkov A., and Zaitsev A. The 1867 Virgin Island Tsunami: observations and modelling. *Oceanologica Acta*, 2003a, vol. 26, No. 5-6, 609 – 621.

Zahibo, N., Pelinovsky, E., Kurkin, A., and Kozelkov, A. Estimation of far-field tsunami potential for the Caribbean Coast based on numerical simulation. *Science Tsunami Hazards*. 2003b, vol. 21, No. 4, 202 – 222.

Young, S.R., Voight, B., Sparks, R.S.J., Rowley, K., Robertson, R.E.A., Lynch, L.L., and Aspinall, W.P. Selected papers on Eruption of the Soufrière Hills Volcano Montserrat. *Geophysical Research Letters*, 1998, vol. 25, No. 18 & 19.